Ground vibration studies of aerospace structures – NAL's contribution

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Ground-resonance testing is an important phase in an aerospace development programme before the flight vehicle is cleared for the actual flight trails. The emerging trends in civil and military aircraft and their requirements from structural-dynamic stand-point have been the basis for the development of various test systems at NAL. Use of new techniques, novel concepts and an integrated systemic approach were the key in these developments. The first task was the development of a six-channel multipoint test system MAMPA. Application of MAMPA to typical rocket wing and other such aerospace structures brought out the importance of signal control, speed of data acquisition, etc. These, together with the all-round progress in digital techniques culminated in the development of CAVITAS (computer-aided vibration test and analysis system). The frequency domain analysis adopted provides distinct advantages in the estimation of structural dynamic characteristics. Concurrently, modal analysis using Laplace domain approach was implemented into the mobile version of CAVITAS.

The success of any test technique, method or system lies in its application. The paper presents various significant studies carried out on a typical fighter aircraft and a low-speed aircraft. Based on the rich experience gained from these studies, the paper focuses its attention on future needs of new techniques in data acquisition, processing and interpretation for civil and defence aircrafts of the country and sets directions for research and development efforts in this all-important area of aerospace vibration.

Introduction

Modern airplane structures tend to be more flexible than those of the preceding decades and this flexibility is fundamentally responsible for the various types of aeroelastic phenomena in the field of aerospace engineering. The structural flexibility by itself may not be objectionable but when additional forces induce further deflections it becomes a matter of concern. The aerodynamic forces may produce additional structural deformations which may induce aeroelastic instabilities. Further, some of these aerodynamic forces are also dependent on the response and these are time-varying. These interactions can give rise to divergence and, finally, lead to a catastrophic failure of the structure. It is such interactions among aerodynamic, elastic and inertial forces which give rise to various aeroelastic phenomena and become important in design[1].

It is also required that the analytical studies are adequately confirmed by testing. The ground vibration testing, as the name implies, is the determination of the vibration characteristics of the structure on the ground but supported in a suitable way to simulate the free–free flight condtion. A knowledge of the dynamic characteristics of a structure is essential due to the fact that an excitation of arbitrary form defined in time would generally excite the structure in its various natural modes. The initial theories of ground vibration testing were based purely on harmonic excitation[2].

Analog methods of ground resonance testing

One of the major problems in structural dynamics is to establish the modes of vibration that a complex structure would have if it contained no damping. These modes will be called *principal modes*; after appropriate normalisation they are referred to as *normal modes*. Trial-Nash[3] suggested a method for systematic adjustment of force levels to determine these normal modes. The properties of a normal mode provide some very useful criteria of purity of modes established and hence could be used in the ground resonance test. Measurement of the phase relationship of the response of the sturcture at several points could readily be accomplished and provides a clear indication of mode purity. A normal mode when excited by appropriate adjustment of force levels and phase difference would, on removal of the excitation force, undergo a smooth sinusoidal decay as there is no coupling with any other normal modes. Often this smooth decay is another criterion of modal purity.

The concept of normal mode excitation by distributing forces in a manner intended to cancel the distributed structural damping forces received attention in References 4 and 5. The establishment of pure normal modes makes possible the separation and definition of modes having frequencies fairly close together. The production of smooth decay curves allows more precise determination of damping coefficients. Achievement of these results, and the saving in time and effort spent in data reduction, may more than offset the additional set-up efforts called for by the use of distributed exciting forces in this experimental approach.

Among the other approaches combining experimental and analytical techniques have been the component analyser techniques[6] and the admittance concept of ground resonance testing. The component analyser technique is based on an experimental determination of quantities which decrease the effects of modal interaction and an analytical separation of modes of vibration using the experimental data. This approach utilizes a minimum of experimental equipment and has, as one of its basic objectives, the reduction of time required for the experimental phase of ground vibration testing. In admittance concept of ground resonance testing, a sinusoidal forcing fuction is applied to each of the points and the resulting complex response is measured at different points, for different frequencies. The resultant data are reduced to yield the admittance matrices from which the normal undamped frequencies and mode shapes can be calculated.

MAMPA – for exciting principal modes

MAMPA system, Figure 1, is a multichannel excitation system which normally applies the necessary force distribution to the structure to make the response at all the excitation points vibrate in phase with one another. The two significant variables, viz., force distribution and excitation frequency are controlled so that the system 'homes' on to the frequency and force distribution that will produce in-phase responses. The system provides up to a maximum number of six excitation stations. MAMPA is capable of fulfilling the requirements of multipoint excitation technique such as (a) phase and force control, (b) in-phase/anti-phase excitation option between the channels, (c) measurement of force at all the six stations, (d) simultaneous monitoring of response at all the six stations, and (e) monitoring of the phase angle between the force input and the response output of the structure at the corresponding six stations.

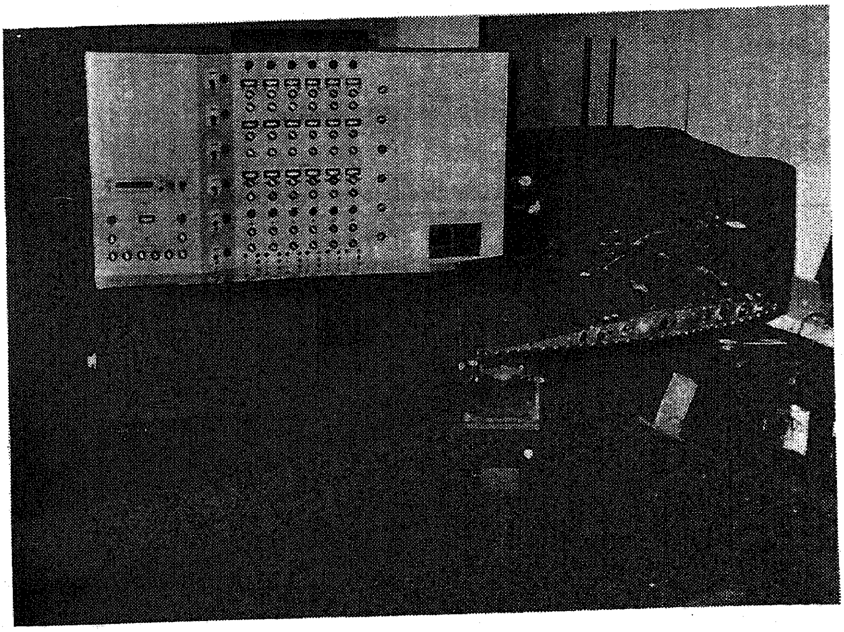

Figure 1. MAMPA system.

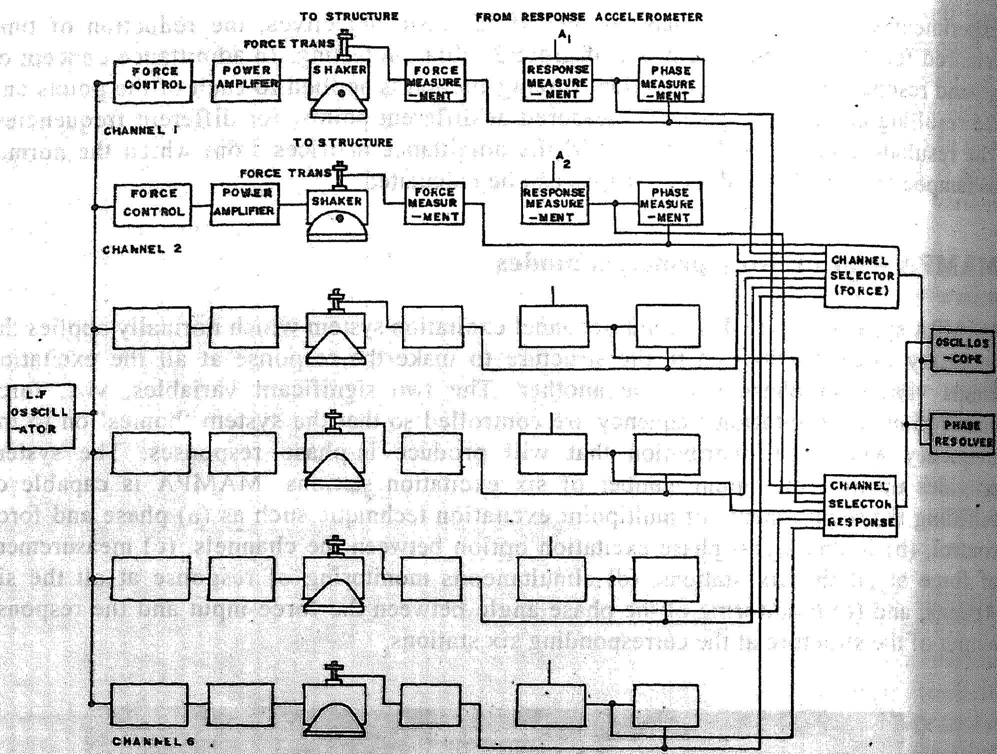

Figure 2. MAMPA – layout.

Table 1. Natural frequencies of rocket wing

Mode no.	Theoretical (influence coefficient method)	Natural frequencies (Hz) Experimental	
		Peak amplitude method	Quadrature phase criterion
1	59.10	57.20	58.40
2	98.20	87.50	89.00
3	153.80	132.50	134.00
4	162.80	171.00	173.00

The layout of the MAMPA system is shown in Figure 2. The electrodynamic vibration generators are attached to the structure under test at selected points. The signal from the oscillator is fed to the power amplifier through the force control unit which drives the

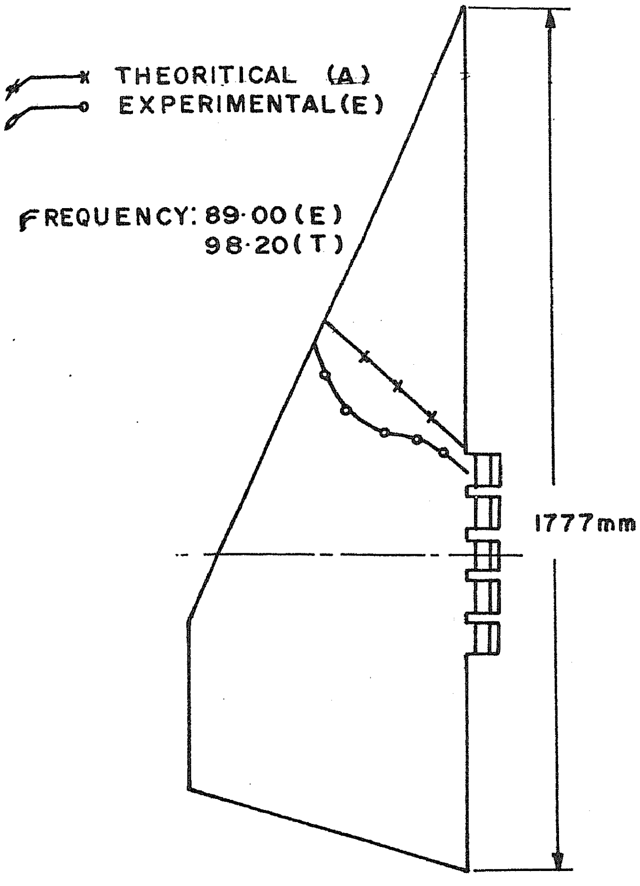

Figure 3. Low aspect ratio rocket wing mode shapes for the second mode.

Table 2. Dynamic characteristics of a wing of typical fighter aircraft

Mode no.	Natural frequency (Hz)		Damping factor	
	SPE	MPE	SPE	MPE
1	14.00	14.2	0.012	0.014
2	46.20	46.90	0.006	0.008
3	91.95	93.60	0.007	0.008

electrodynamic vibration generators. The amplitude and phase of the driving force can be measured using the force transducer introduced between the structure and the shaker. structural response is sensed by the accelerometers mounted on the structure. The signal from the accelerometers are fed to the response measurement unit, which gives direct read-out of acceleration and displacement. The response of the structure and the force input to the structure are fed to the phase measurement unit which gives direct read-out of the phase in degrees. Necessary output terminals are made available for display and record.

MAMPA applications

Rocket wing dynamic studies

The design considerations of a rocket wing structure, among other things, are governed by the aerodynamic loading and guidance and control requirement. While the former

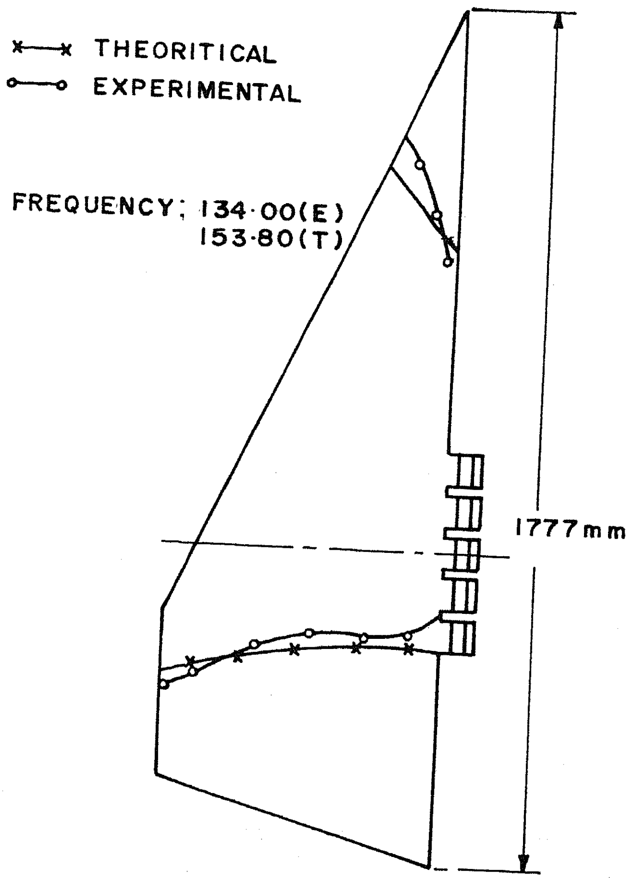

Figure 4. Low aspect ratio rocket wing mode shapes for the third mode.

stipulates the strength consideration, the latter calls for strict control of dynamic characteristics. With these in view, a design exercise of a low aspect ratio rocket wing using indigenous material has been undertaken.

The theoretically calculated and experimental values of the natural frequencies are presented in Table 1. The mode shapes are presented in Figures 3–5. The first mode is along the root. There is good agreement between the theoretical and experimental values for the first two natural frequencies. It should be noted that the partial fixity allows slight rotation and hence, the influence coefficient method has predicated slightly higher values for the higher modes. There is very good agreement among experimental values. Mode shapes also compare well. These tests also validate MAMPA functions.

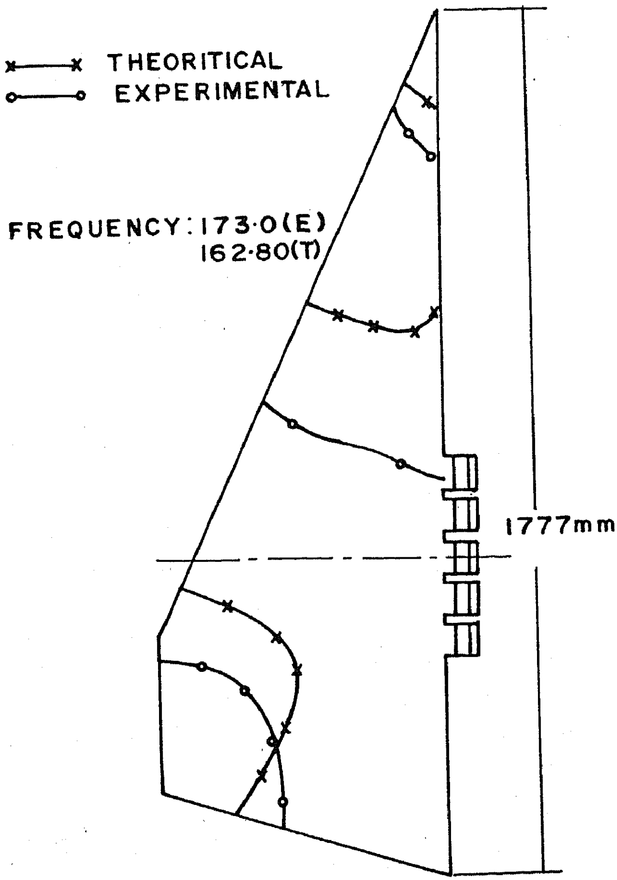

Figure 5. Low aspect ratio rocket wing mode shapes for the fourth mode.

Supersonic fighter aircraft wing vibration test

The wing of a typical fighter aircraft, Figure 6, was chosen as the second application using MAMPA. The first three modes were studied using single and multipoint excitation techniques. The natural frequencies and damping factors have been evaluated. The results are compared and presented in Table 2. The agreement is fairly good. Thus, once again, the analog system MAMPA developed has been exploited satisfactorily.

CAVITAS – computer-aided vibration test and analysis system

Having established the conventional analog vibration test methods and with the advent of digital computers and related digital electronics, the obvious evolution is to combine the best of hardware and software aspects to design a computer aided vibration test and analysis system (CAVITAS). The basic step involved in this process is to arrive at a system requirement which is dictated by the applications. The second step is to choose the basic logic for different inputs. The third step would be to evolve the various algorithms that are required in the implementation of the logics. Hardware development, particularly the interface system, is a very important task, since the analog and digital communications are through this system. Finally, the software for analysis, not only the conventional time series analysis packages but also the special-purpose software for on-line estimation of the concept of flutter from the flight data are to be developed. The protection software to control the excessive levels of vibration excitation, the hardware elements of

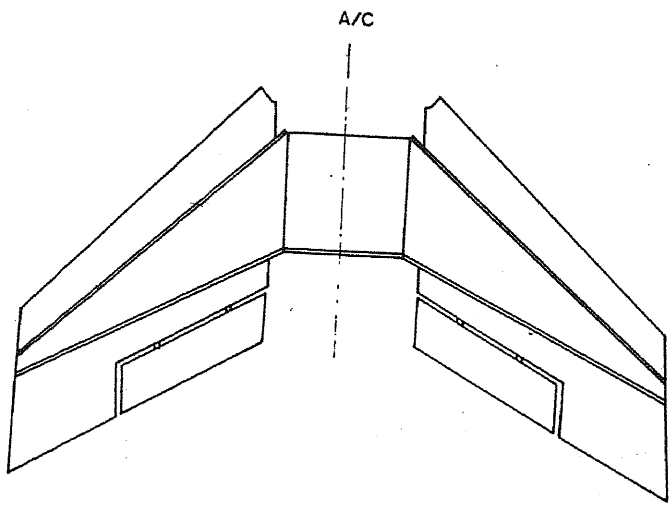

Figure 6. Fighter aircraft wing (plan_form).

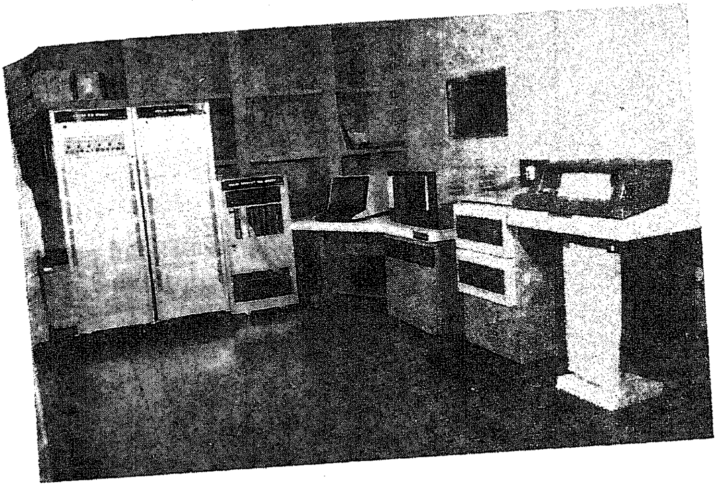

Figure 7. CAVITAS.

Table 3. Dynamic characteristics using CAVITAS

Wing study results

Mode no.	CAVITAS application: SPE* P/A	SPE* Phase	MPE†	Mode description
1	16.50	17.0	17.8	Bending (symmetric)
2	22.00	22.8	22.2	Wing torsion
3	28.50	29.2	29.8	Bending (antisymmetric)

Horizontal tail results

Mode no.	CAVITAS application: SPE* P/A	SPE* Phase	MPE†	Mode type
1	24.5	24.0	23.8	Bending (symmetric)
2	27.0	26.0	26.5	Bending (antisymmetric)

*Single point excitation
†Multipoint excitation

the system and finally the test documentation would put together the development of the CAVITAS.

Experimental studies using CAVITAS

Wing and horizontal tail-plane dynamic testing

Employing the CAVITAS (Figure 7) wing and horizontal tail-plane dynamic characterisics have been evaluated. For this purpose both the single and multipoint excitation methods have been employed. The natural frequencies using SPE have been identified by peak amplitude and quadrature phase criterion. These results are presented in Table ... The nature of the modes are also presented.

Modal analysis of a typical fighter aircraft

The modal analysis of the complete aircraft has been carried out employing the transient excitation using an instrumented hammer. In all 139 points were chosen for the transient excitation, (Figure 8). In each of the test locations an average of 20 recordings were taken for a reasonable statistical accuracy. For the mode identification step, the modal

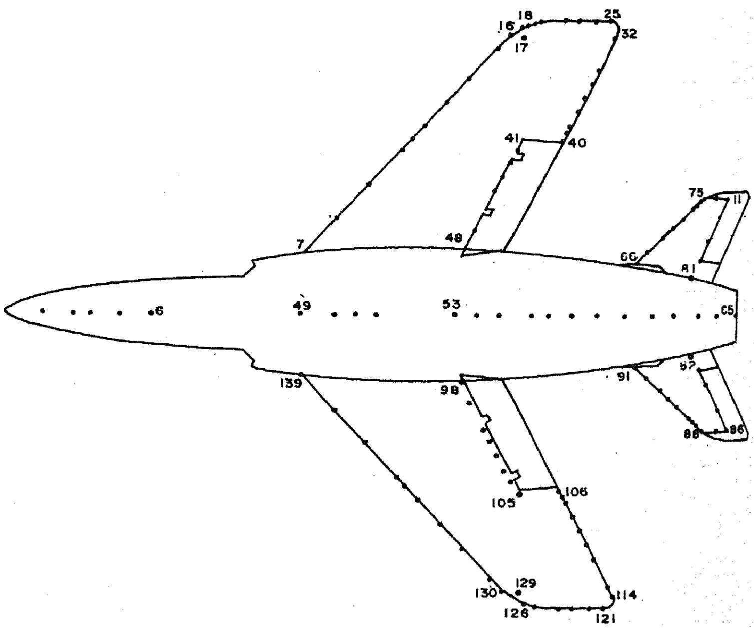

Figure 8. Transient response locations.

Table 4. Fundamental frequencies of the A/C components and the aircraft

Aircraft component	Fundamental frequency (Hz) Calculated	Modal analysis	Remarks
Wing	18.824	16.11	Bending (symmetric)
Fuselage	25.26 (FEM)	25.78	Bending
Horizontal tail	24.278	22.18	Bending
Complete aircraft	20.56 (FEM free free)	22.18	

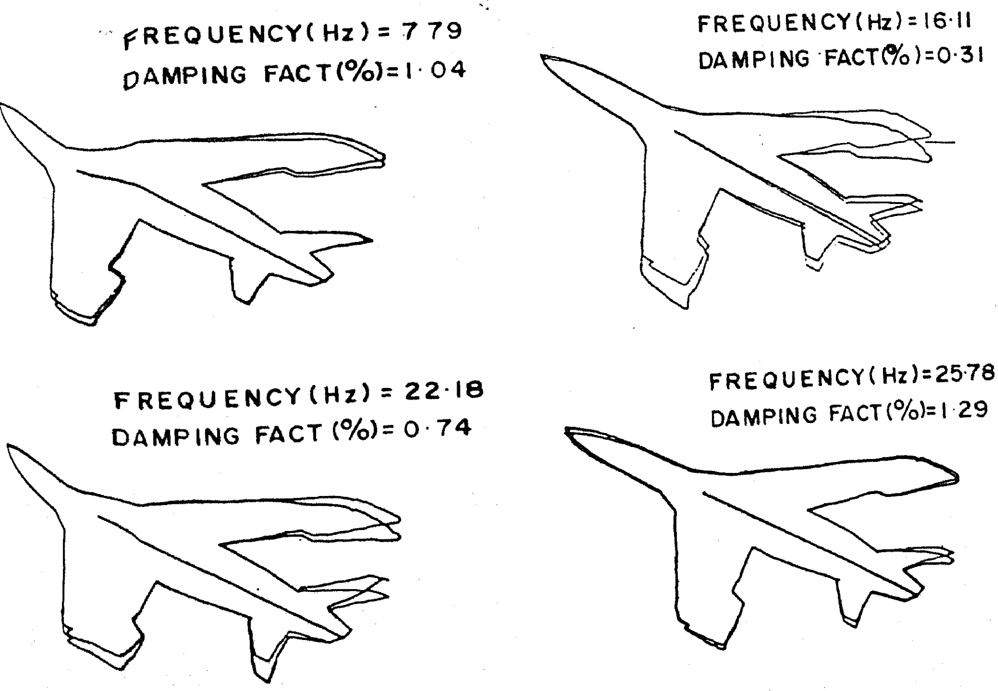

Figure 9. Modal analysis of the aircraft.

parameters in each transfer function are estimated. This allows a significant amount of user control over the identification process so that accurate modal data are obtained from the measurement. Making use of the data on individual aircraft components like wing, rear fuselage and horizontal tail, the fundamental modes have been generated and compared

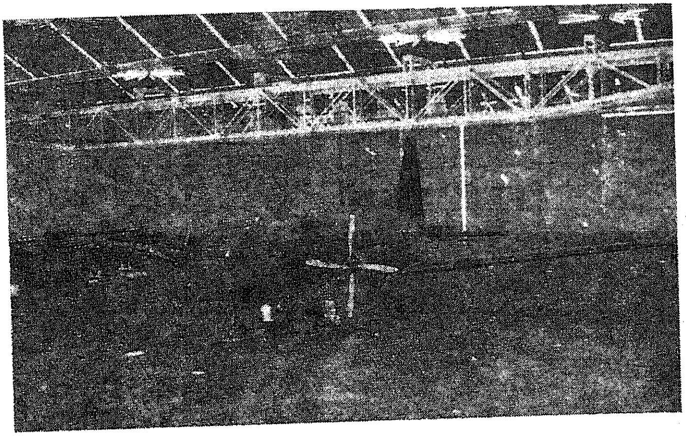

Figure 10. Low-speed aircraft for vibration test.

Table 5. Comparison of experimental results (low-speed A/C)

Mode	Frequency (Hz) Sine	Random	Modal analysis
Wing bending and fuselage symmetric bending	3.64	3.67	3.67
Fuselage torsion	–	–	4.79
Wing bending anti-symmetric	7.53	7.63	8.23
Tail bending symmetric	9.66	8.23	9.86
Wing fuselage tail bending	13.27	13.45	13.45

with the analytical estimation and these are presented in Table 4. Mode shape plots presented in Figure 9, where the modal damping values are also stated.

The results generated using CAVITAS on the structural components of the aircraft different method agree well (Table 3). These also compare well with the modal analy results in Table 4. The FEM calculation has predicted slightly higher values for the w and horizontal tail which could be attributed to the fact that the tyre characteristics (un deflected condition) are not taken into account while simulating and boundary conditi With regard to the complete aircraft, the FEM calculation is for free–free bound condition and, hence, is lower than the modal analysis result. The modal mass, stiffn and damping values generated have been made available for subsequent aeroelas

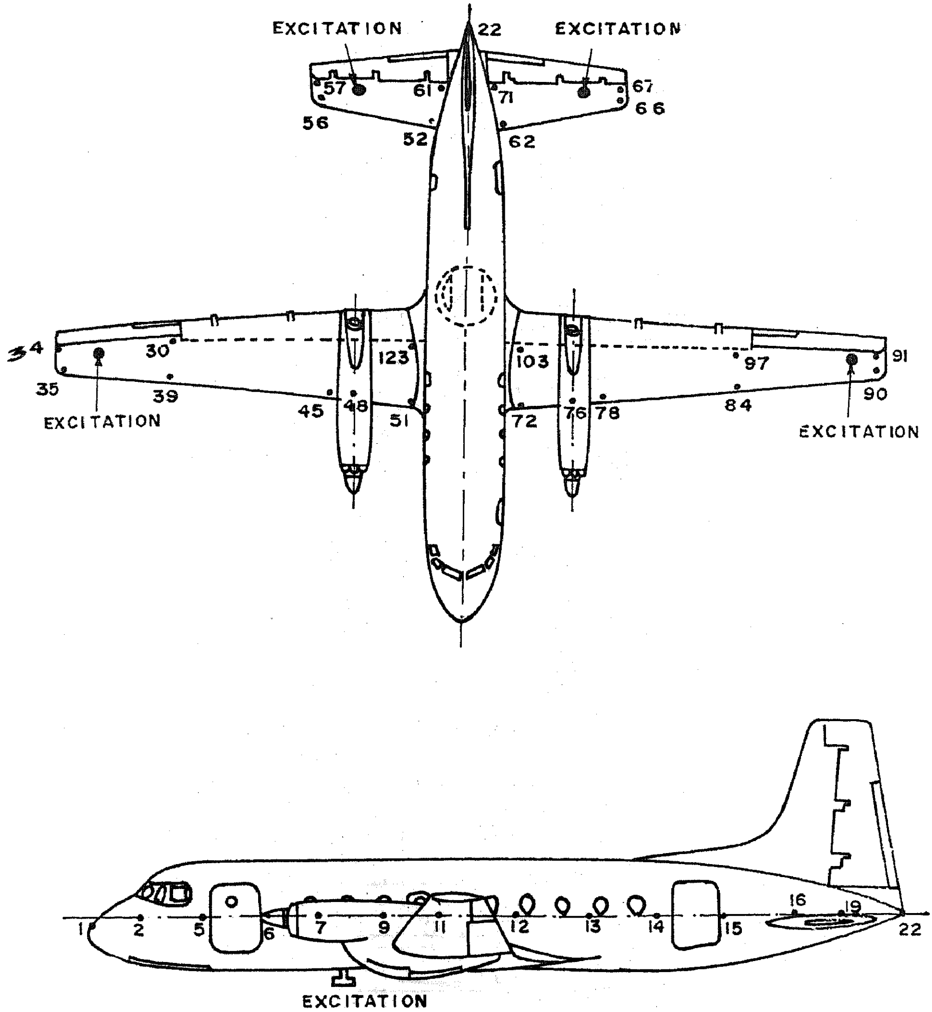

Figure 11. Excitation and response location for ground vibration testing (sine input).

calculations. This study provided a good confirmation on various features of hardware/ software incorporated in the CAVITAS.

Ground vibration studies of a low-speed aircraft

As a first step, sine excitation was given to wing, fuselage and tail plane (Figure 10). The responses were measured at various locations indicated in Figure 11. The natural

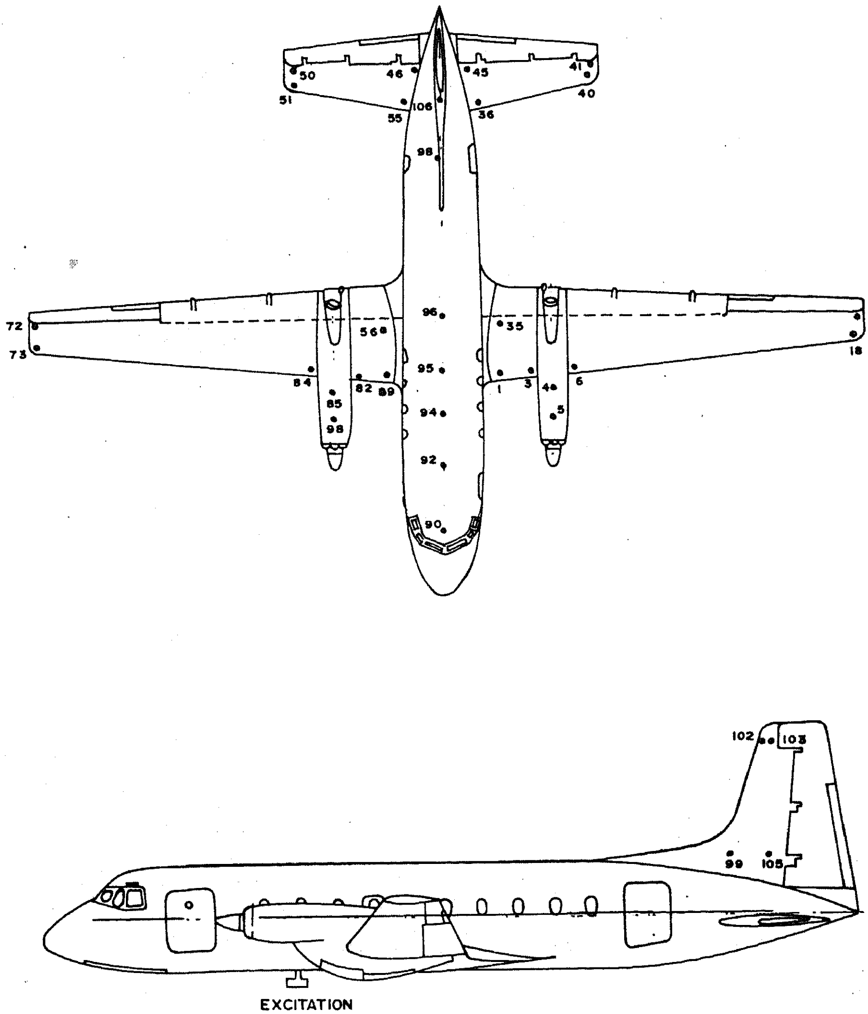

Figure 12. Excitation and response location for random vibration testing.

frequencies were found using single and multiple excitations. The random excitation was provided using a single exciter of appropriate force rating at the intersection of bulkhead station about 1.9 m from the reference C.G. location towards the tail. A band-limited random input was given and the response measured on the points distributed over the aircraft, as shown in Figure 12. The response analysis was carried out using ba selectable Fourier analysis. About ten averages of the response signal were taken at each of the response locations. Based on the coherence criterion between the input and output, these response signals were accepted for per spectrum analysis. Zooming the peaks on the response power spectrum, the exact natural frequencies were identified for the fuselage, wing and tail plane.

The results of the sine and random vibration tests are presented and compared with the modal analysis results. (Table 5). The various mode descriptions are also stated in the table. It should be noted that there is, in general, agreement among the various methods.

Conclusions

The paper brings out the importance of the ground vibration studies of aerospace structures and the significant developments like MAMPA, CAVITAS, etc., carried out at NAL. The applications of these systems to actual aerospace structural components presented in the paper not only validate the methods and techniques but also the results obtained are significant.

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